Integrating PBEE and Network Analysis to Measure Resilience Performance Objectives

STANFORD URBAN RESILIENCE INITIATIVE

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Earthquake Resilience

- Resilience agencies (e.g., [1]) have published "current" and "target" regional resilience performance of key city infrastructure after an earthquake scenario (see Fig. 1). The resilience performance explicitly considers the two dimensions of the recovery process: functionality and time after the earthquake.
- Previous regional risk estimation techniques (e.g., HAZUS [2]) built initial robust methodologies for assessing expected values of earthquake consequences.
- Currently, there is no systematic methodology for probabilistic quantification of regional resilience performance objectives that integrates new advances in earthquake engineering (e.g., spatially correlated ground motion modeling) and network analysis, which enables the modeling of key dependencies of urban systems identified as significant in the NIST resilience planning guidelines [3].
- The proposed methodology aims to integrate the advances in earthquake engineering and network analysis in order to assess "current" and "target" regional resilience performance of key infrastructure such as the ones outlined in Fig. 1.

TARGET STATES OF RECOVERY FOR SAN FRANCISCO'S BUILDINGS AND INFRASTRUCTURE

INFRASTRUCTURE CLUSTER FACILITIES	Event occurs	Phase 1 Hours			Phase 2 Days		Phase 3 Months		
		4	24	72	30	60	4	36	36+
CRITICAL RESPONSE FACILITIES AND SUPPORT SYSTEMS									
Hospitals								X	
Police and fire stations			X						
Emergency Operations Center									
Related utilities						X			
Roads and ports for emergency				X					
CalTrain for emergency traffic					X				
Airport for emergency traffic				X					
EMERGENCY HOUSING AND SUPPORT SYSTEMS									
95% residence shelter-in-place								X	

Figure 1. "Current" (in blue) and "target " (in X) performances in San Francisco after a Mw 7.2 on the San Andreas Fault. The "current" performance was assessed by expert opinion (Source: [1]).

Objectives and Scope

- The objective of this research is to provide an analytical framework to support ongoing community resilience planning initiatives, incorporating the analysis of built environment vulnerabilities and key urban interdependencies as outlined in [3].
- This poster describes the proposed framework that uses a probabilistic approach to measure "current" resilience performance and assesses the likelihood of reaching community scale Resilience Performance Objectives (RPO) (e.g., performance targets in SPUR) by utilizing and drawing inspiration from the modular analysis of Performance Based Earthquake Engineering (PBEE) and explicitly incorporating network analysis of interdependent urban systems.
- This framework does not attempt to refine or advance specific risk or network analysis techniques, but to provide a way to unify current resilience, network and risk research and channel it towards helping decision makers measure resilience goals.

Framework: steps for evaluating RPO's

The framework has been broken down into 7 steps. Fig. 2 provides a graphical representation of the analysis workflow.

Model Definition

Step 1: Identify the stakeholder, resilience performance measure, referred to as Resilience Decision Variable (RDV), and RPO. The RPO is the target performance with two dimensions: RDV threshold reached at a target time after the earthquake. *Ex. RDV: number of functional hospitals [1], RPO: 100% functioning 24 hrs after the earthquake.*

Step 2: Define hazard level for the RPO. *Ex. earthquake scenario that corresponds to a shaking level with 10% chance of occurrence in 50 years [1].*

Step 3: Identify relevant urban components. In this context, urban components refer to all the buildings and network systems that need to be considered to quantify the RDV. Then, identify the interdependencies among the urban components. *Ex. Urban components for hospital functionality: hospital buildings, water network (pumps, pipelines and reservoirs), wastewater network (pipelines, pumps, treatment plant), and power network (power plants, and power lines and substations). Interdependencies: pumps (for the water network) require power (from the power network) to function [3].*

Step 4: Identify appropriate fragility functions for the urban components that are susceptible to earthquake damage.

Step 5: Identify urban components' recovery curves, while considering impeding factors, correlation and constraints, where appropriate.

Numerical Analysis

Step 6: Modeling of the urban system under earthquake stress:

Regional risk
- Model earthquake rupture and ground motions, considering spatial correlation.
- Model individual urban components' damage states, for components that are susceptible to damage.
- Model individual urban components' recovery times, given a damage state.

Network analysis
- Model the functionality of the interdependent urban network. The most recent developments take into account explicit treatment of dynamic network interdependencies [5].
- Quantify RDV's distribution at each time step after the earthquake.

Step 7: Quantify the probability of meeting the RPO and the time required to meet the RDV threshold with a specified confidence level.

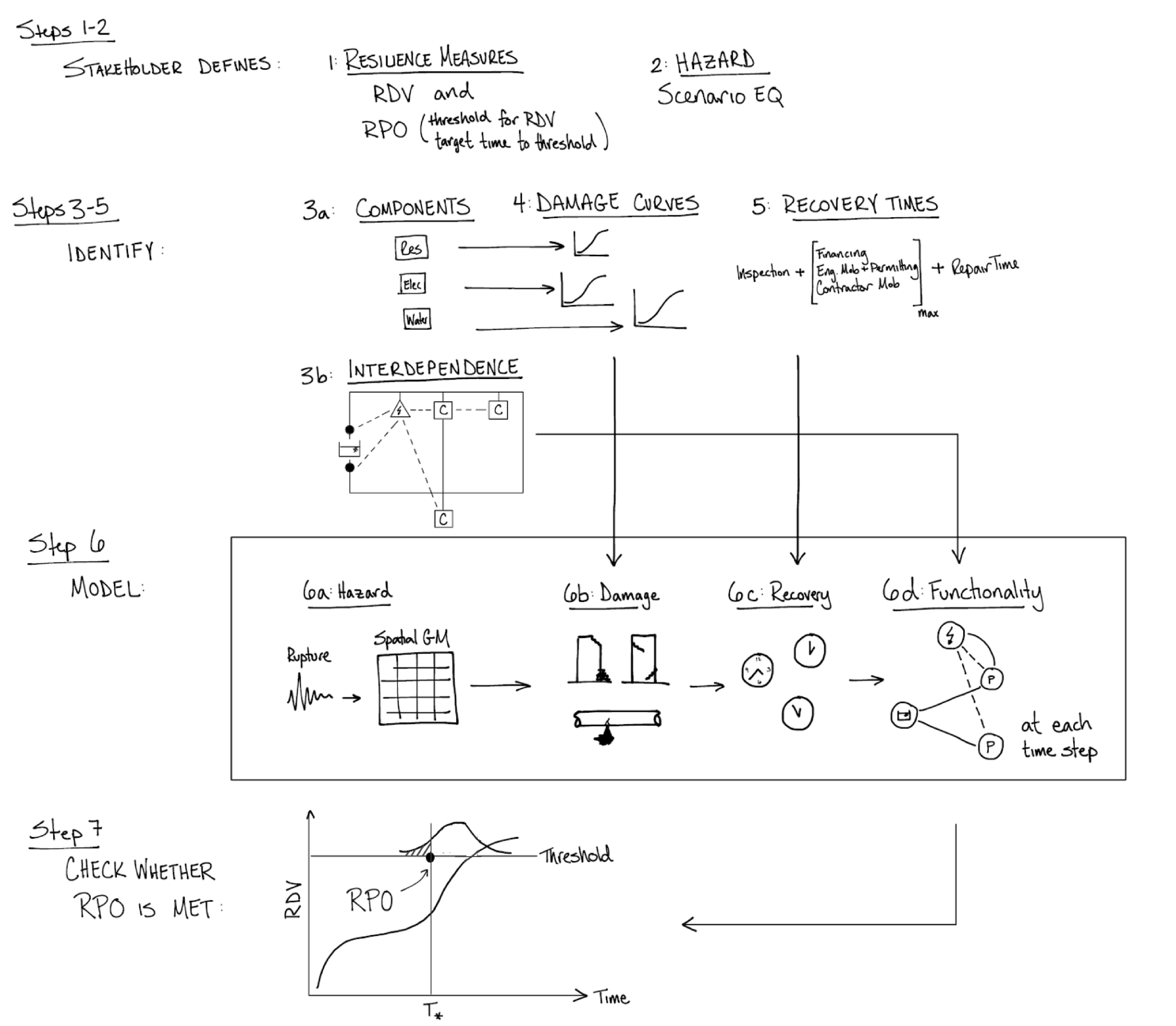

Figure 2. Schematic representation of the steps for Resilience Performance Objective quantification.

Proof of concept: measuring shelter-in-place availability

This case study exemplifies the usability of this framework. In this example, shelter-in-place is defined as a building that is undamaged or is repaired with access to water. The analysis is done for a Mw 7.0 earthquake that affects 3 communities. The following gives a brief description of the analysis steps.

Step 1:
- Stakeholder: the municipality and the tenants.
- RDV: percentage of housing units that can function as shelter in-place (building repaired + water and wastewater systems functioning).
- RPO: 95% of housing units, 24 h after the earthquake.

Step 2: Earthquake scenario of Mw 7.0. The ground motion is simulated for a 70x25 km area with a resolution of 1x1km

Step 3: (see Fig. 3)
- Building stock: 3 communities (C1, C2, and C3 denoted by green triangles) with 30 buildings each comprised of 3 types of reinforced concrete buildings with different number of stories.
- Water network (in blue): one water reservoir that delivers water through two main pipes with corresponding pumps to the communities, the thermoelectric plant and the substation.
- Power network (in red): the thermoelectric plant delivers power to the substation, and then the power is distributed to the pumps, the wastewater treatment plant and to the communities.
- Wastewater network (in magenta): The wastewater from the thermoelectric plant and the communities is pumped to a treatment plant.

The urban networks are interdependent.
- The thermoelectric plant (power net.) requires water (from water net.) for cooling and functional wastewater network.
- The pumps (water and wastewater net.) need power (from power net.) to work.

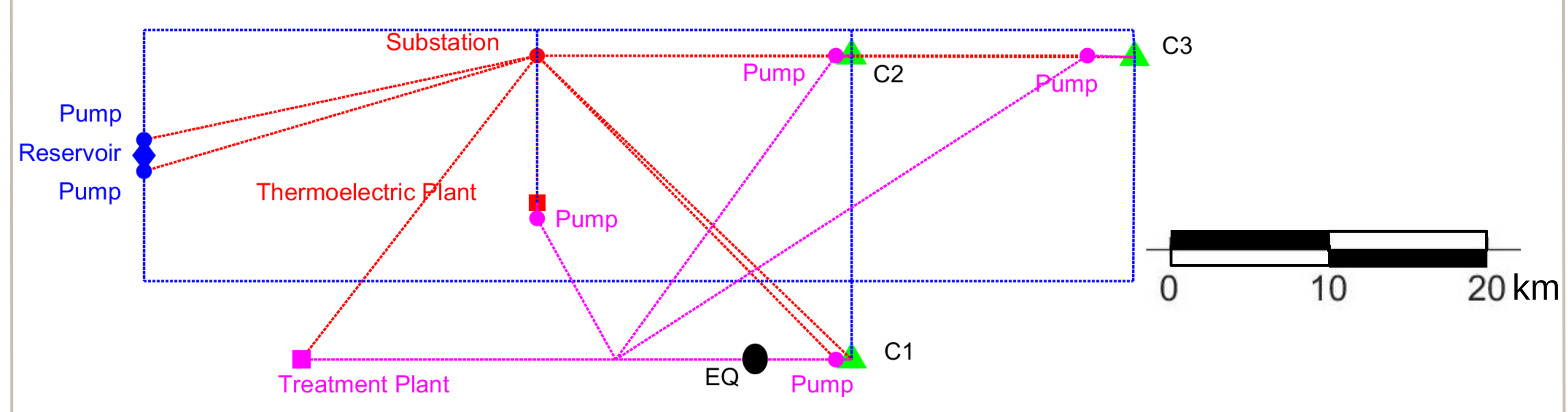

Figure 3. Earthquake scenario (in black) and built environment: 3 communities (in green), water (in blue), power (in red), and wastewater (in magenta) networks.

Step 4: All the buildings and network components shown in Fig. 3 and described in Step 3 (except for the electric power lines) are considered susceptible to damage and have associated fragility functions selected from [2], [6], [7].

Step 5: Recovery paths defined according to HAZUS and the REDi procedure.
- For buildings, in addition to physical repair times, impeding factors such as inspection, engineering mobilization, contractor mobilization, financing, and permitting were included.
- Network components' recovery times are modeled as per [2] methodology and they do not include impeding factors.
- For a given community, correlation in the recovery times of buildings was considered by sampling recovery time associated impeding factors of buildings in different damage states from a multivariate lognormal distribution with a correlation coefficient of 0.5.

Step 6: Modeling of the urban system under earthquake stress.
- Sample different realizations of correlated ground motions (see Fig. 4).
- Sample damage states and recovery times for each urban system component, considering correlation where appropriate.
- Apply network analysis to each realization of the dynamic interdependent network to verify delivery of water to the 3 communities at each time step after the earthquake.

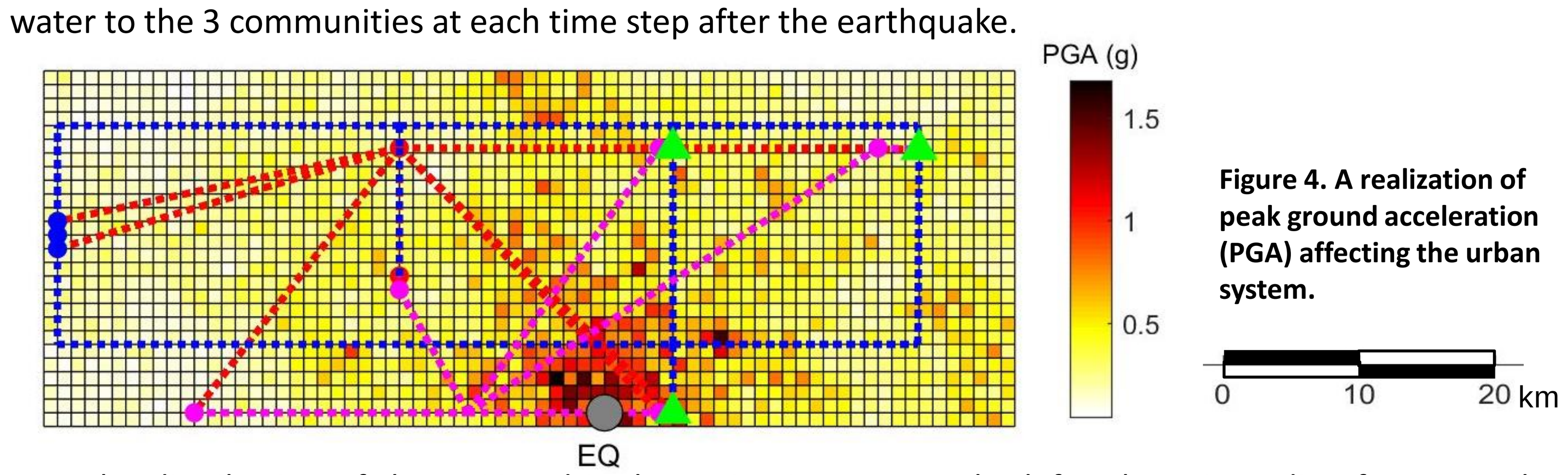

Figure 4. A realization of peak ground acceleration (PGA) affecting the urban system.

Step 7: The distribution of the RDV and is shown in Figure 5. To the left, where impeding factors in the recovery are considered, the "current" performance is far below the resilience "target" (RPO). No realization met with the RPO, and the 80% central confidence interval revealed that 95% shelter in-place is reached between 1.2 and 3.2 years. This striking mismatch between the "current" and "target" is similar to the expected shelter in-place performance in San Francisco (Fig. 1). To the right, where impeding factors are not considered, no realization met the RPO, and 80% central confidence interval was 0.20 to 1.1 years.

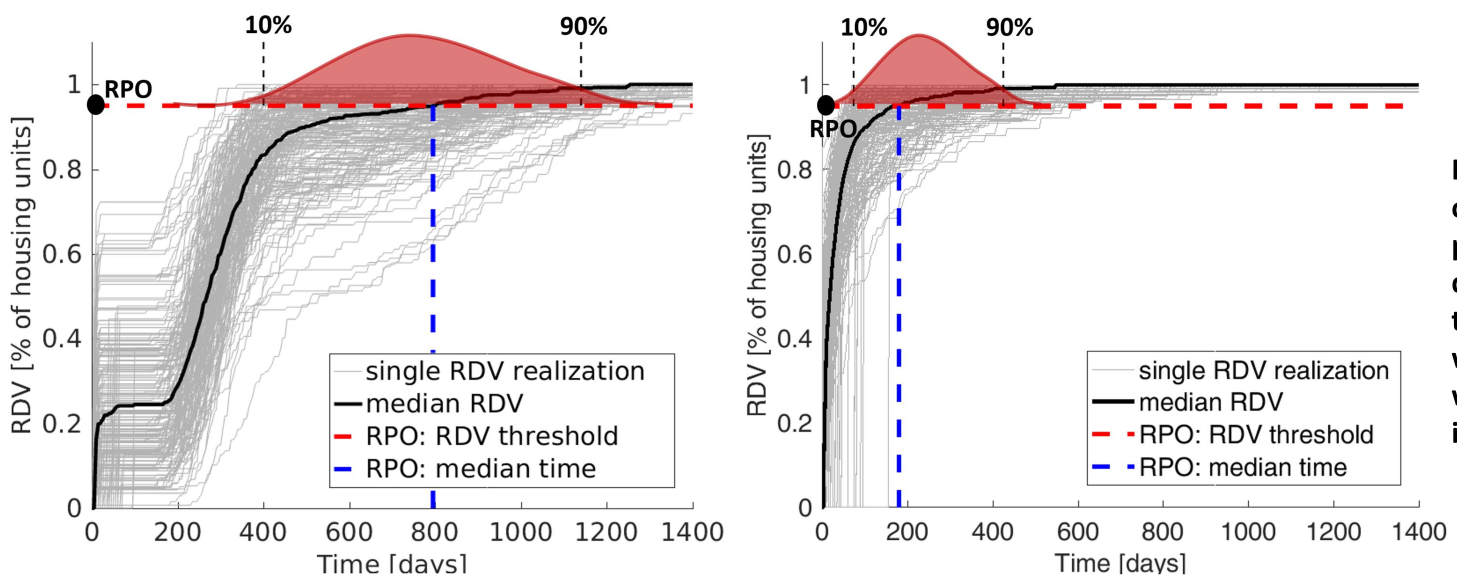

Figure 5. RDV (% of shelter in-place units) distribution after the earthquake with (left) and without (right) impeding factors.

Summary and Continuing Work

A probabilistic framework for assessing "current" and "target" regional resilience performance of key urban functions was presented. This framework combines recent advances in earthquake risk analysis and network analysis to provide probabilistic quantification of performance and assess the likelihood of achieving resilience performance objectives (RPO) in an urban system under the stress of an earthquake. The framework is composed of 7 steps that go from the model definition through to the model analysis. A proof of concept example is presented to demonstrate the applicability of the framework and to show the relevance of the results. The example showed the relevance of the impeding factors on the recovery. Continuing work will include:

- Extension of the case study to real communities and networks in order to verify that the presented methodology scales to a larger, more realistic urban system.
- Analysis of the most contributing factors, or 'bottlenecks' in recovery process, as related to meeting RPO.
- Development of data driven correlation models for buildings' impeding factors, as more recovery data becomes available.
- Inclusion of impeding factors in network systems' recovery and introduction of repair sequencing in distributed networks.

References

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